Putting a spin on speckle: the twisted way magnets remember.

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Multicycle and nanopillar work:

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Coherent X-ray work

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Magnets according to CM theorists

Different levels of detail, (i.e. correctness):

- Quantum mechanics: Start with the actual atoms and try to calculate microscopic quantities, e.g. anisotropy and coupling. Drawbacks: Hard to do and doesn't tell you about evolution on mesoscopic length scales

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- Landau-Lifshitz-Gilbert (LLG) equations: Provides a detailed description of the classical dynamics. It models both precession and damping of spins given a local Hamiltonian for the magnet. Drawbacks: Takes a long time to run making it difficult to make real-world predictions.

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- Cellular Automata models. Advantages: Runs real fast and makes nice screensavers

Justification for throwing away terms

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“Universality”

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Does it apply to hysteretic behavior in magnets?

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For the next 5 minutes, I'll take a departure from reality and consider hysteresis in Ising spin glasses.

Multicycle spin dynamics

Consider the 3d Edwards and spin glass Hamiltonian

$$\mathcal{H} = -\sum_{\langle i,j \rangle} J_{i,j} S_i S_j - h \sum_i S_i .$$

- The couplings $J_{i,j}$ are uniform random numbers between ± 1.
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Use single spin-flip dynamics. At any step, we search for the next value of h where a spin flip occurs. Once that happens we let any subsequent avalanches occur before changing h again.

Multicycle spin dynamics

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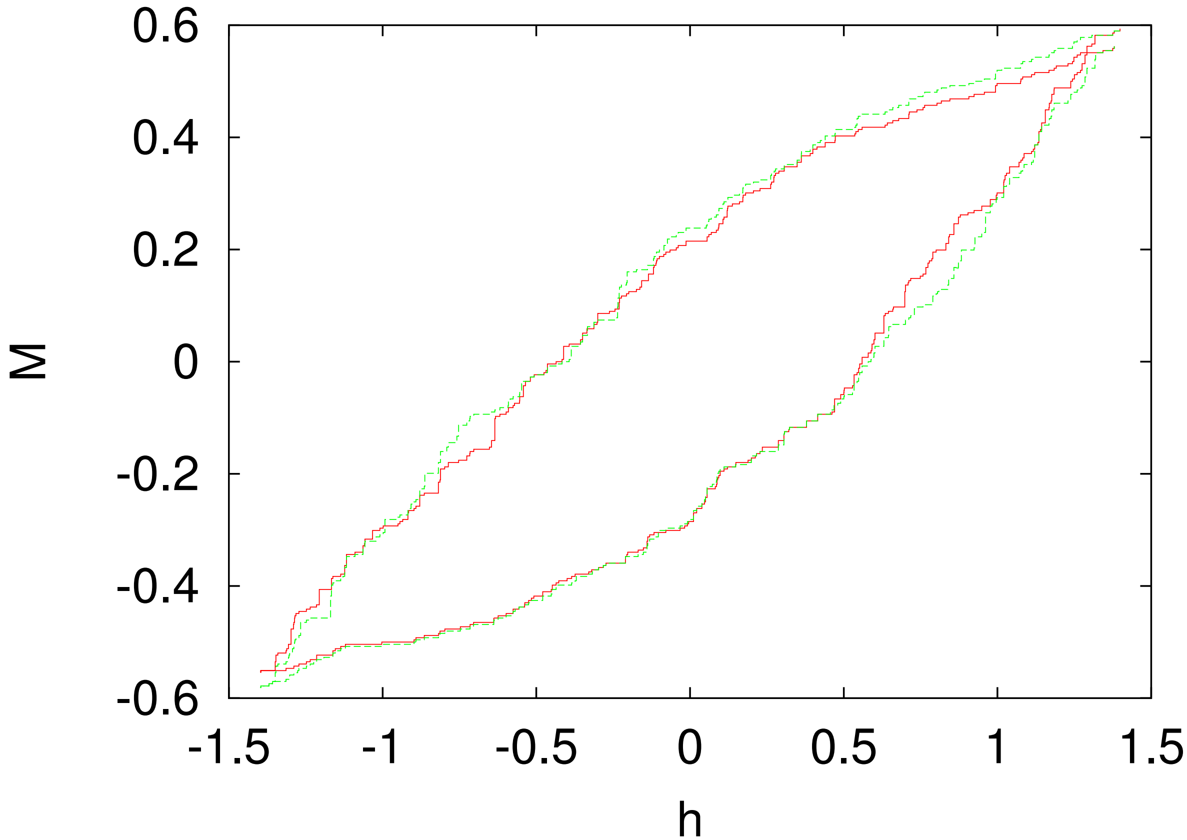
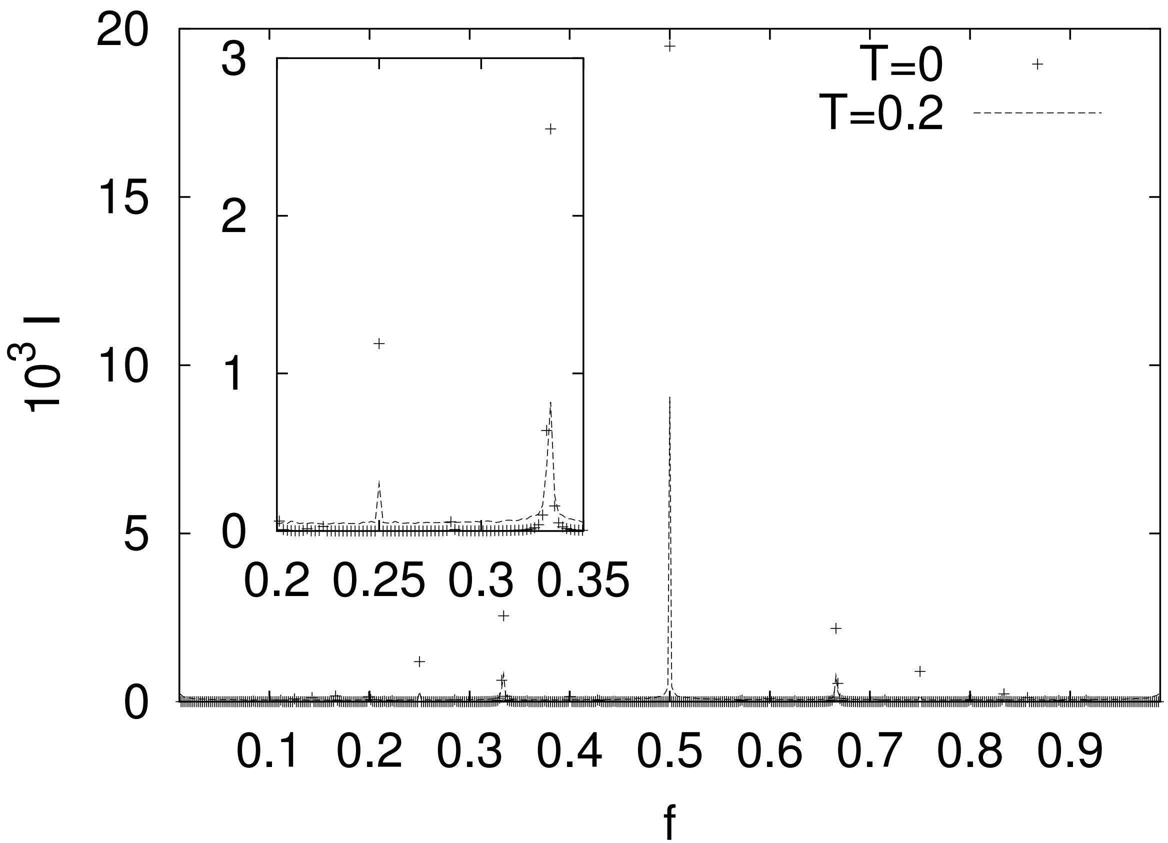
In steady state, the hysteresis loop takes more than one cycle to close on itself.

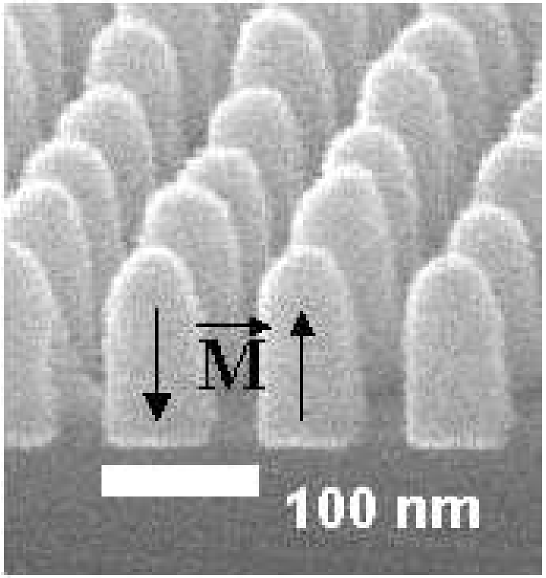


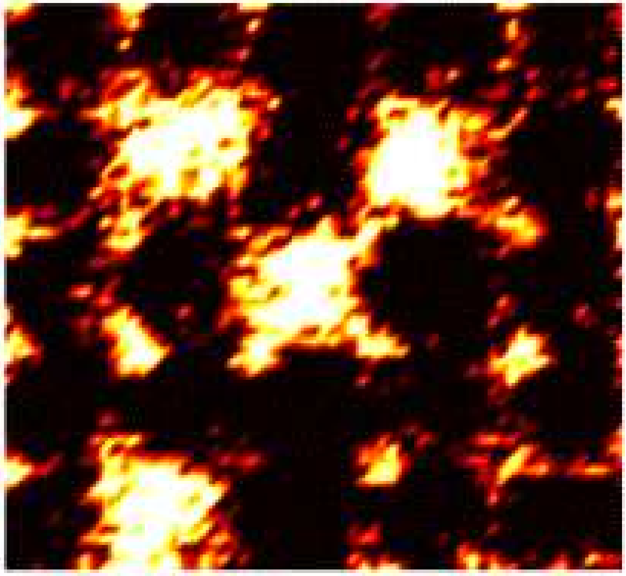
Power spectrum

The magnetization as a function of time in steady state shows subharmonics. The power spectrum of $M(t)$ has peaks at fractions of the driving frequency. (Driving frequency $= 1$ below).



Nanomagnetic pillar arrays





Ni nanomagnets on silicon[1] Magnetic Force Microscopy

[1] Courtesy of Holger Schimdt. Fabricated by T.Savas MIT

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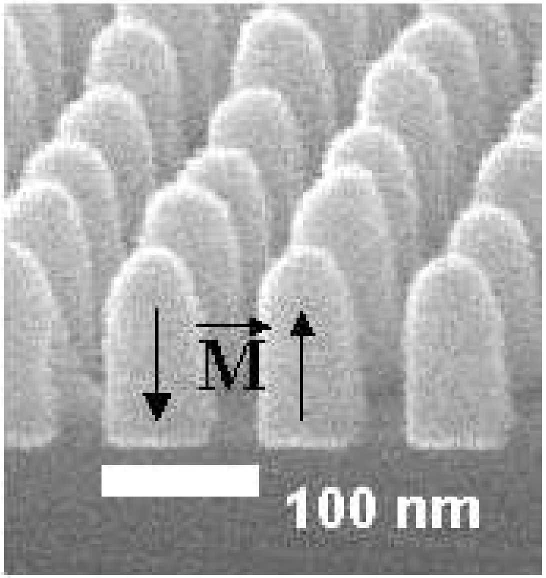

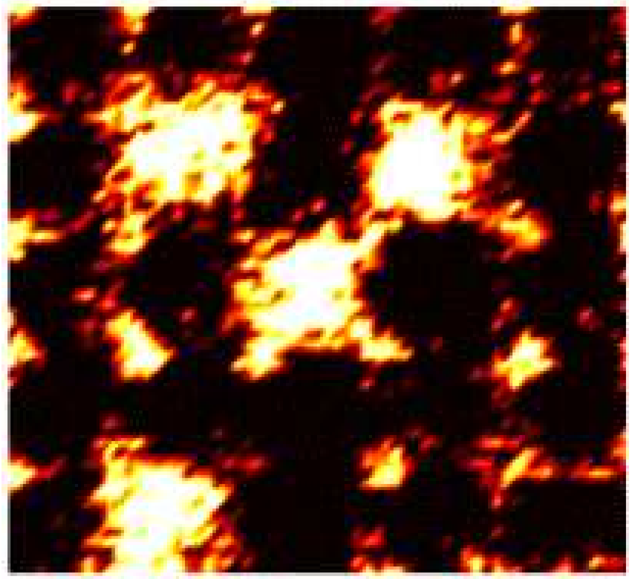

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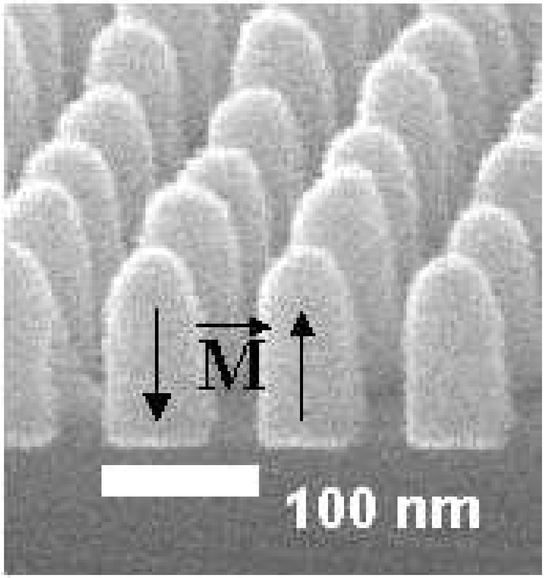

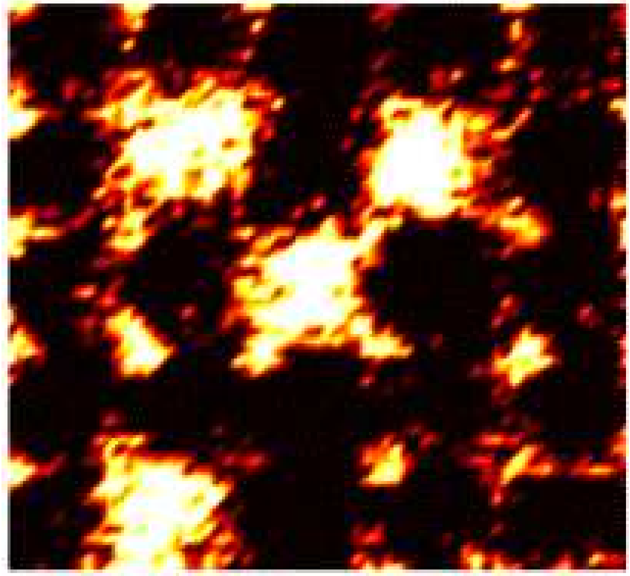

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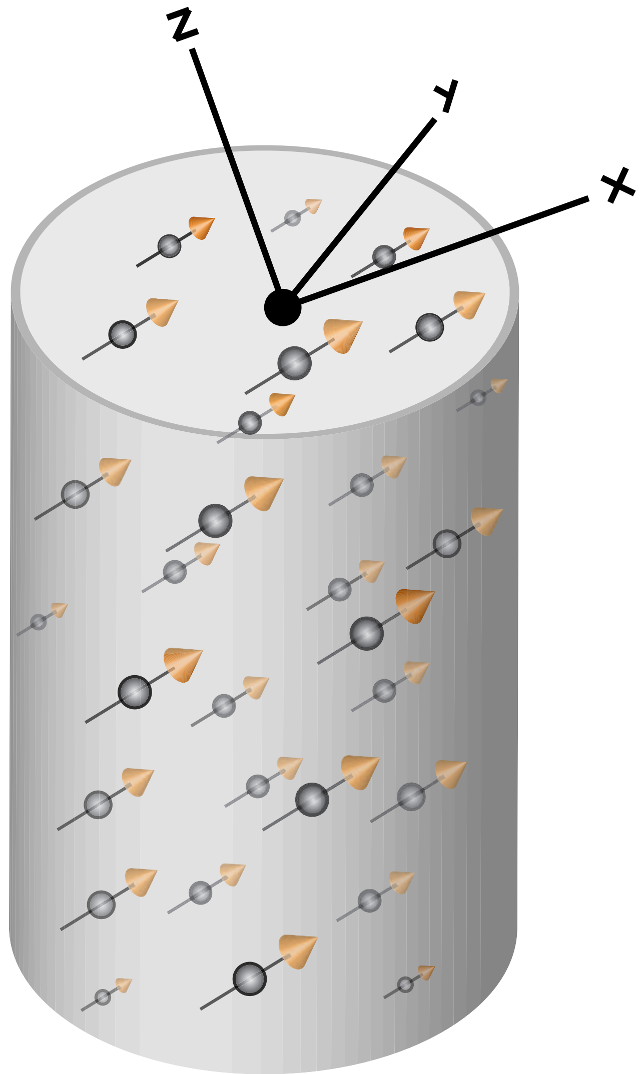
Can such a system show multicycles?

Modeling nanomagnetic pillars

These are single domain nanomagnets where the crystalline orientation is random in each pillar.



Modeling nanomagnetic pillars

The LLG equation describes micromagnetic dynamics. It contains a reactive term and a dissipative term:

$$\frac{d\mathbf{s}}{dt} = -\gamma_1 \mathbf{s} \times \mathbf{B} - \gamma_2 \mathbf{s} \times (\mathbf{s} \times \mathbf{B}),$$

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- γ_2 is a damping coefficient.
- The effective field is $\mathbf{B} = -\partial \mathcal{H} / \partial \mathbf{s} + \zeta$, where $\mathcal{H}$ is the Hamiltonian and ζ represents the effect of thermal noise.

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The Hamiltonian is the addition of four pieces due to:

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- Dipolar self energy, that is *shape* anisotropy: $-\sum_i d_z s_{z,i}^2$
- Dipolar interactions between pillars:

$$\sum_{j \neq i} \mathbf{s}_i \cdot \mathsf{A}(\mathbf{r}_{ij}) \cdot \mathbf{s}_j$$

Results

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It would also be interesting to pursue the possiblity of designing these arrays to perform computation, by making celluar automota.

Non-complementary major loops

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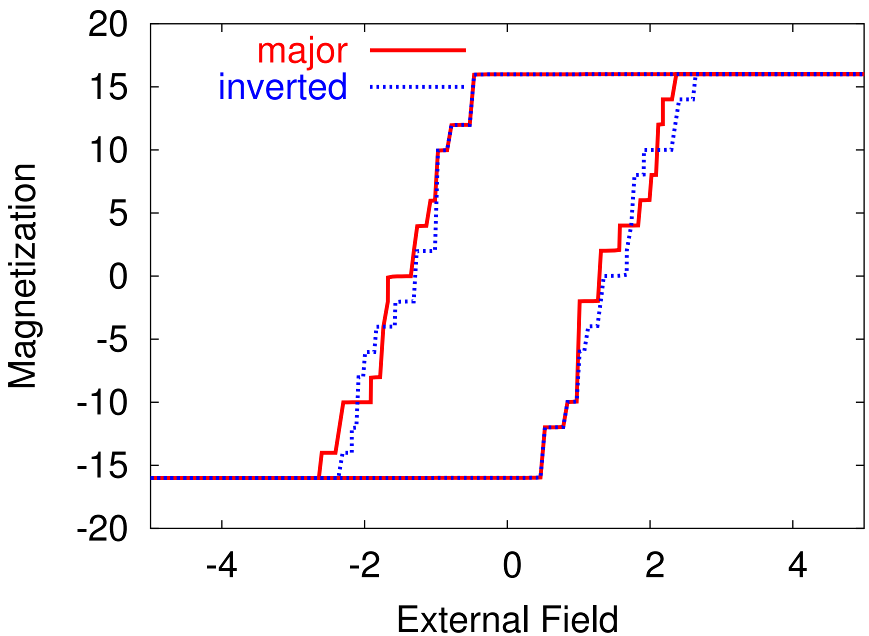

The major hysteresis loop for this model is not complementary!

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MISTAKE:

- Leaving out the precessional nature of the dynamics.

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How does it change under inversion?

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Therefore the dynamics do not preserve spin inversion symmetry.

More fundamentally, this can also be seen from the fact that although the Hamiltonian has spin inversion symmetry, the spin commutation relations (e.g. $[S_x, S_y] = i\hbar S_z$), change sign under spin inversion.

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We'll simulate the LLG equations with the following ingredients in the Hamiltonian:

- Assume the films are disordered but strongly anisotropic. The easy axis is randomly oriented but strongly biased perpendicular to the film.

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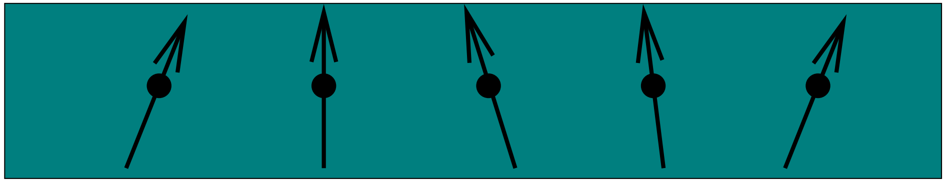

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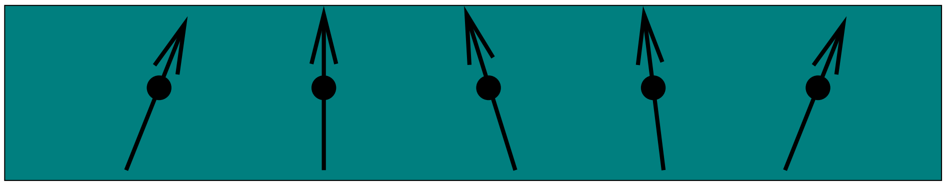

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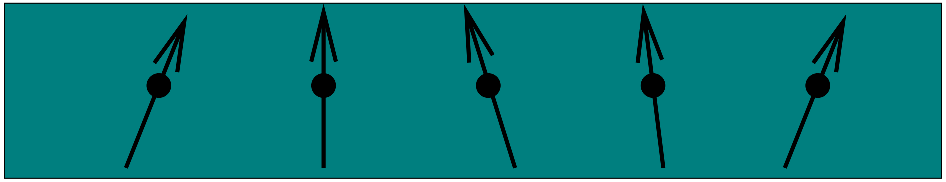

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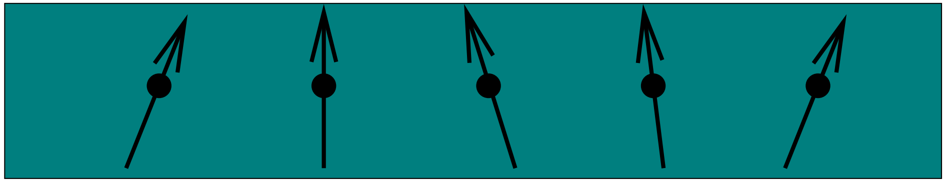

- Assume a long range dipolar interaction between points.
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- The usual interaction with an external field hs_z.

Definition of RPM and CPM

The un-normalized covariance between two spin configurations is defined as:

$$cov(i,j) = \langle \mathbf{s}_i(\mathbf{r}) \cdot \mathbf{s}_j(\mathbf{r}) \rangle_r - \langle \mathbf{s}_i(\mathbf{r}) \rangle_r \cdot \langle \mathbf{s}_i(\mathbf{r}) \rangle_r$$

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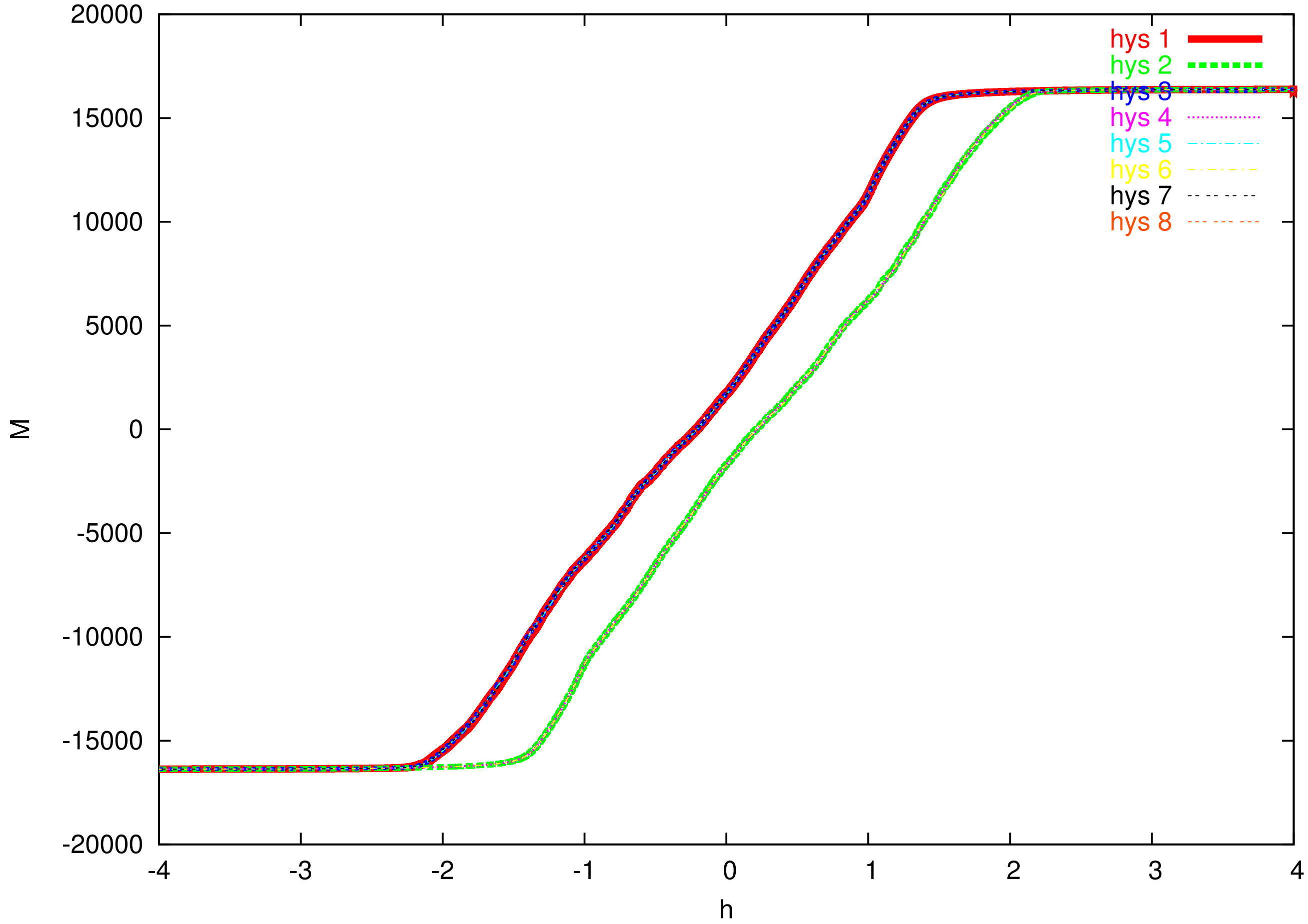
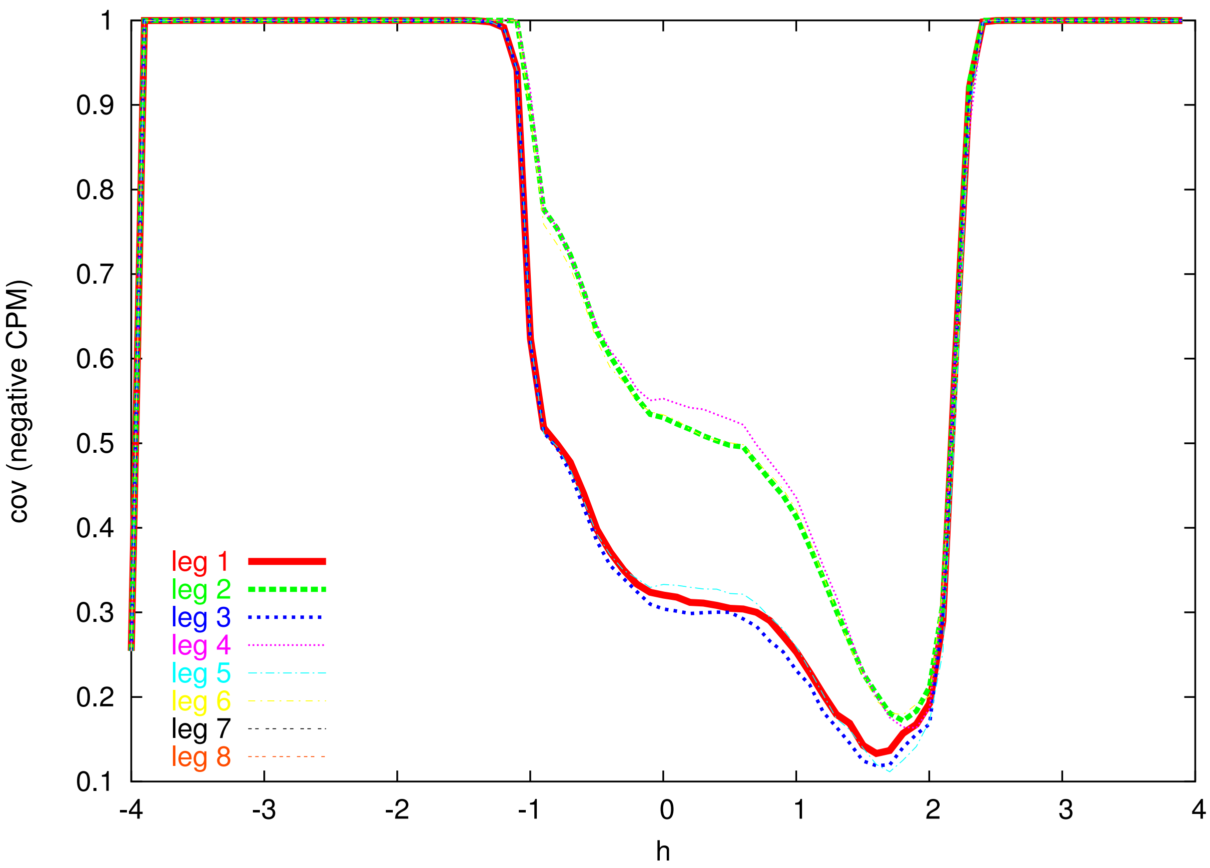
The CPM normalized covariance is $\rho(h,i;-h,j)$ where i and j are legs going in *opposite directions*.

M vs h

For a 128×128 system:

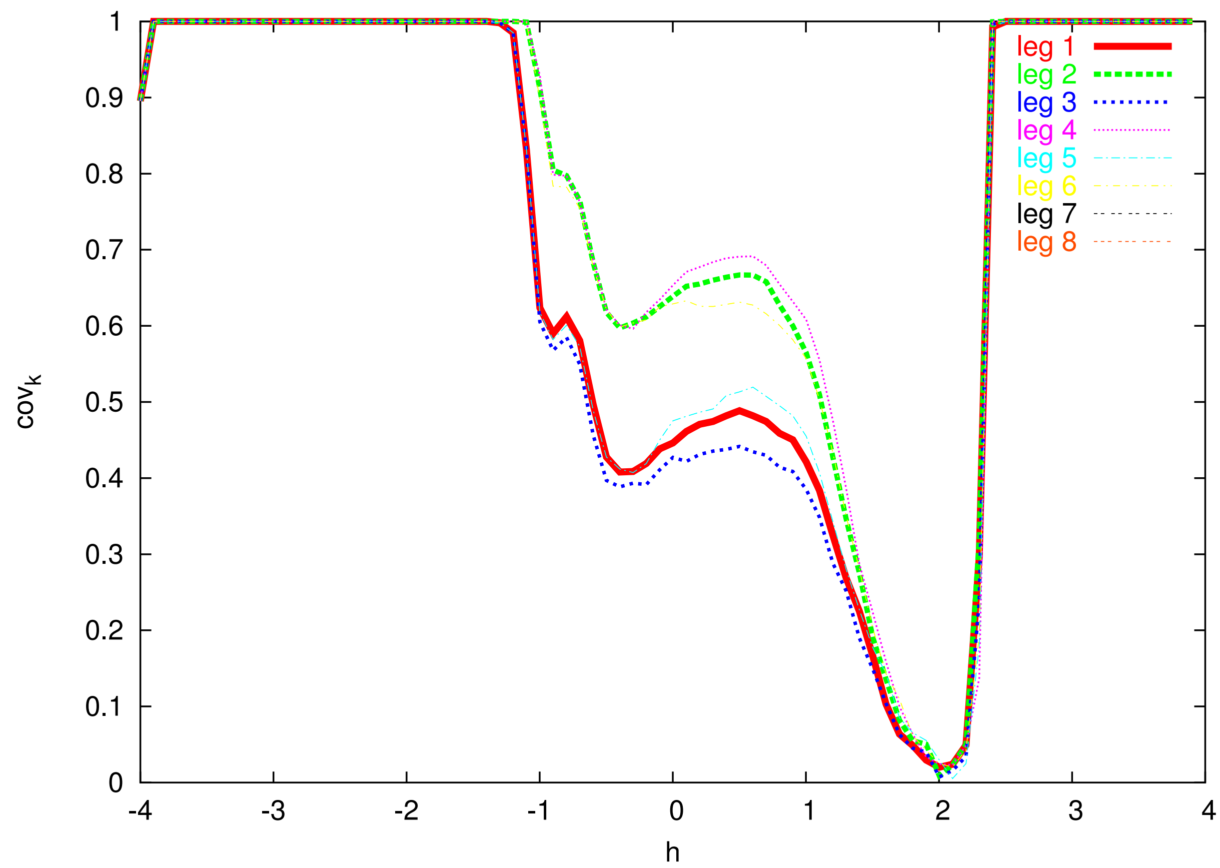


Real space RPM/CPM



k-space RPM/CPM

With the analogous definition for ρ but substituting s for $|\hat{s}_z(\mathbf{k})|^2$

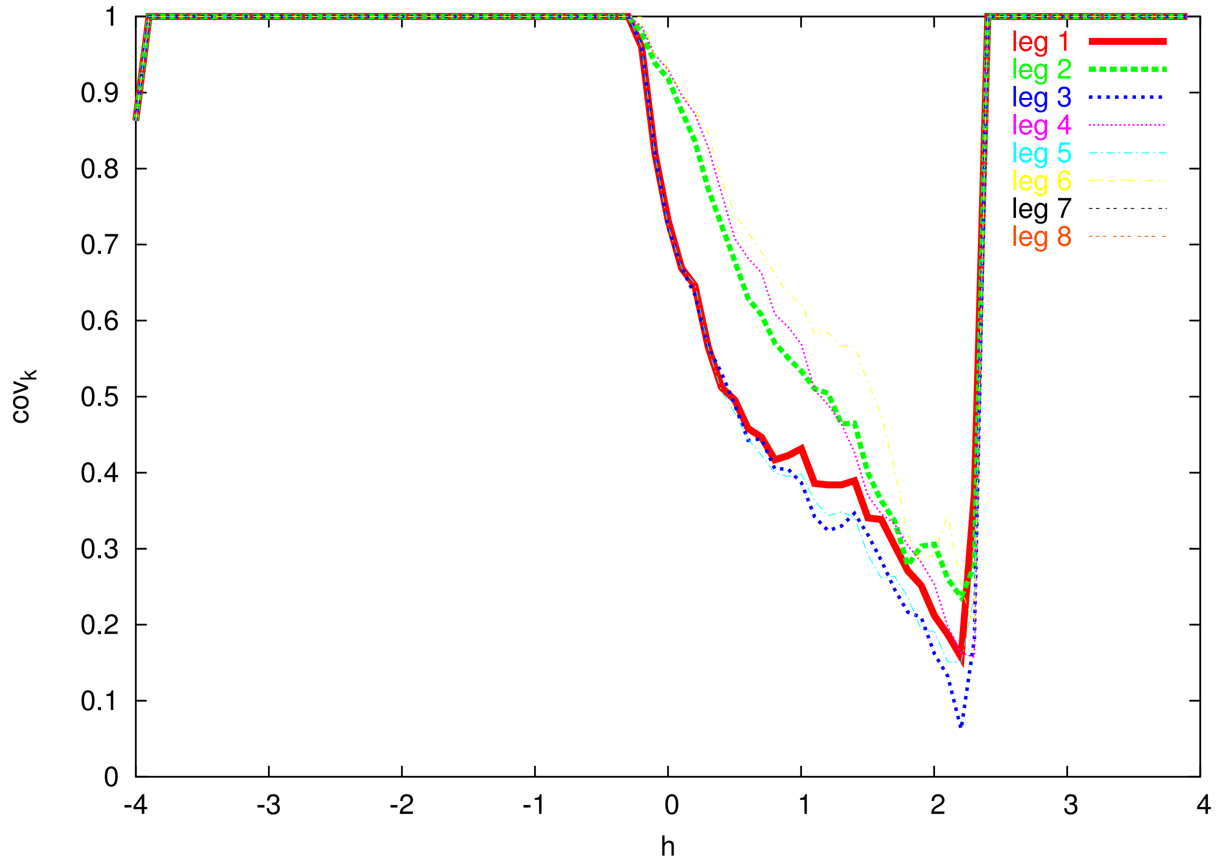


How robust is this?

If the temperature is too high, this effect goes away. The RPM/CPM curves are non-zero but coalesce.

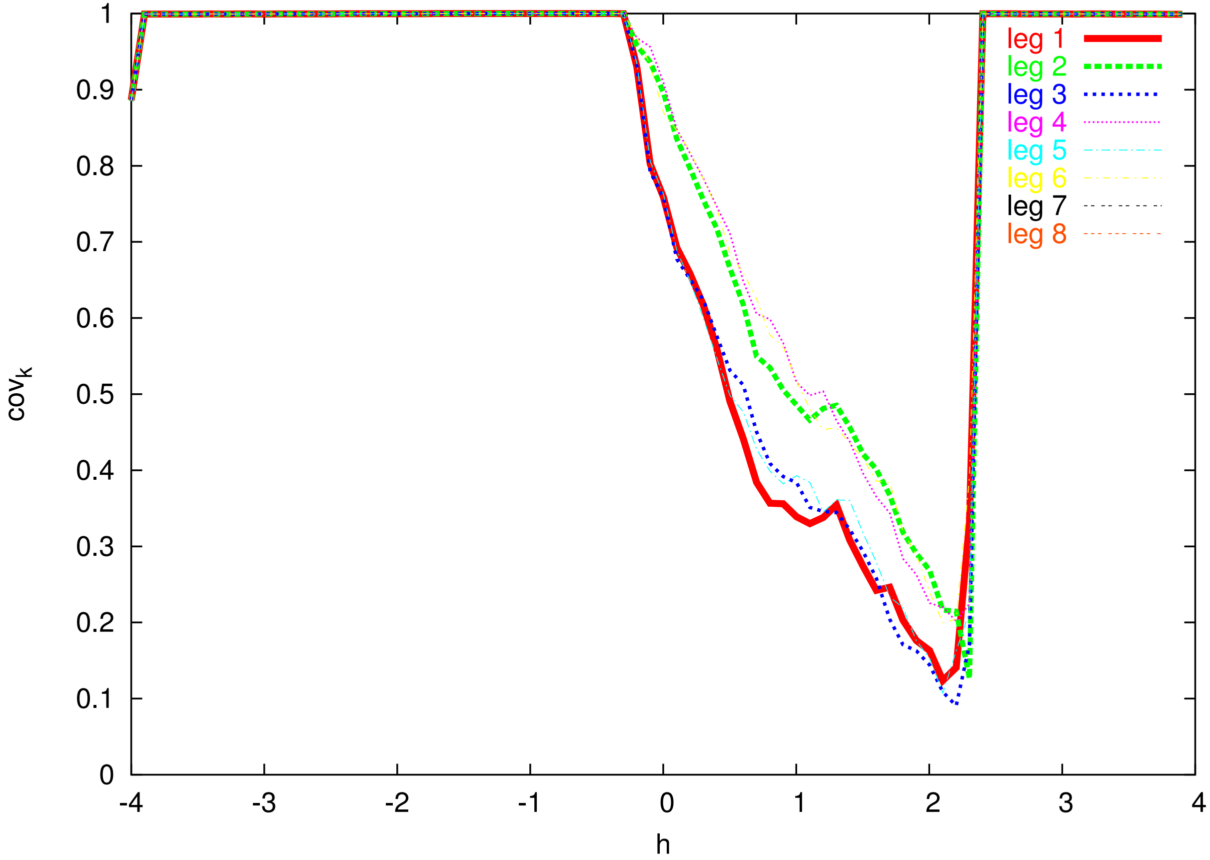
Lowest temperature

T_0 64×64 system.



$\times 10$

$10T_0$



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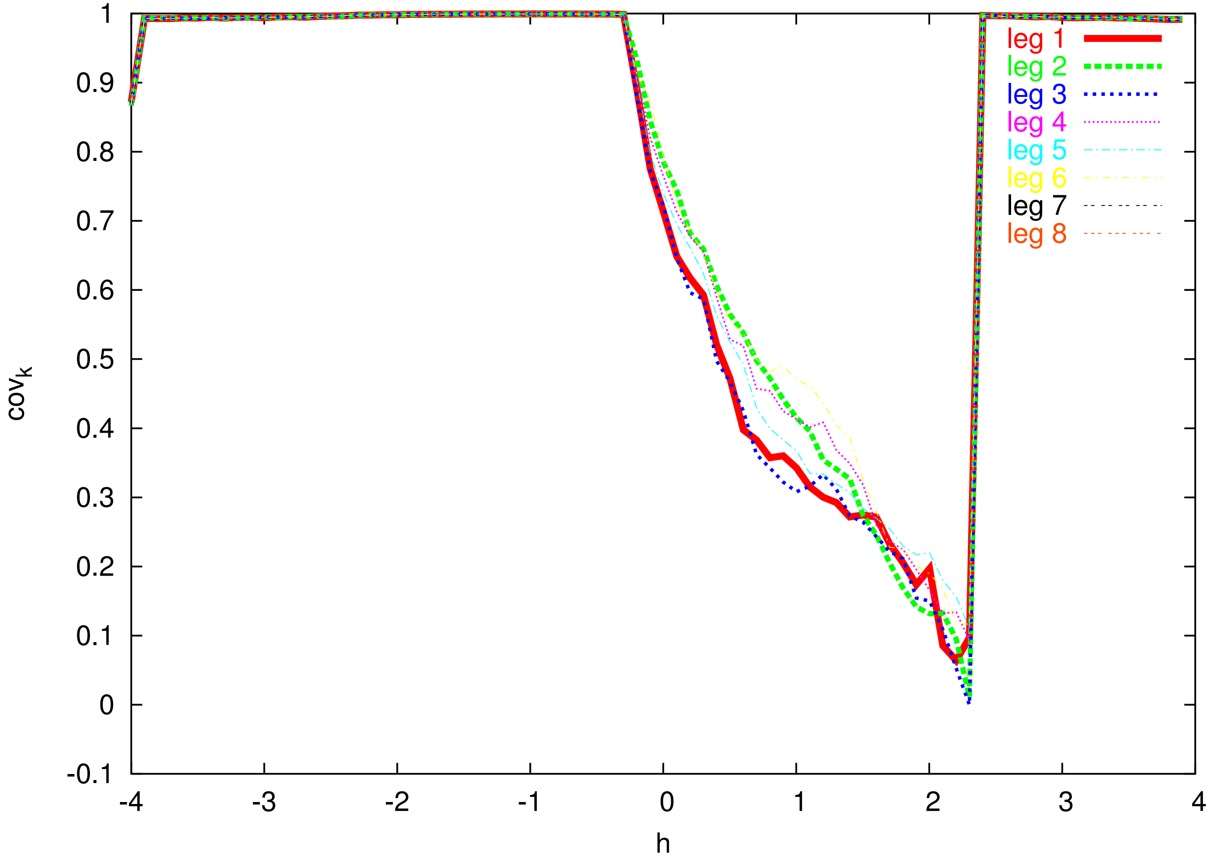
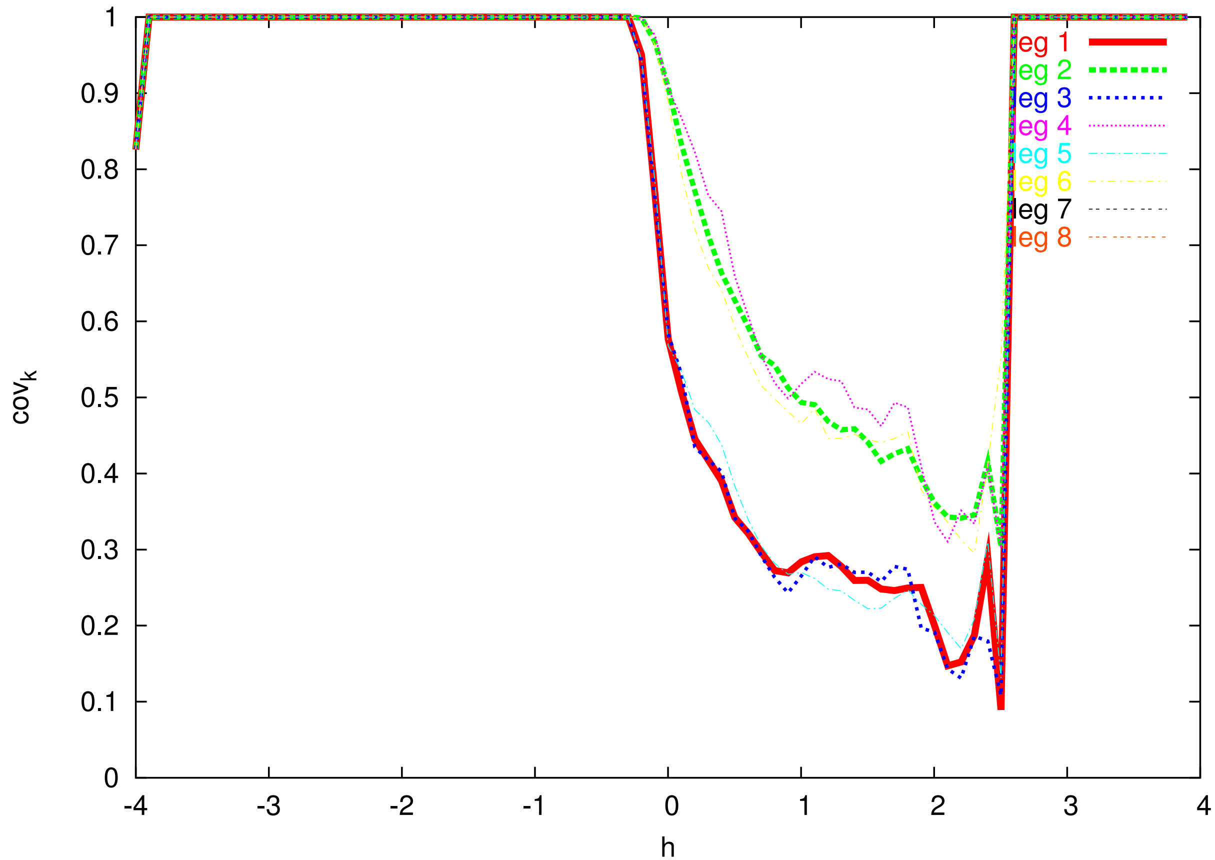


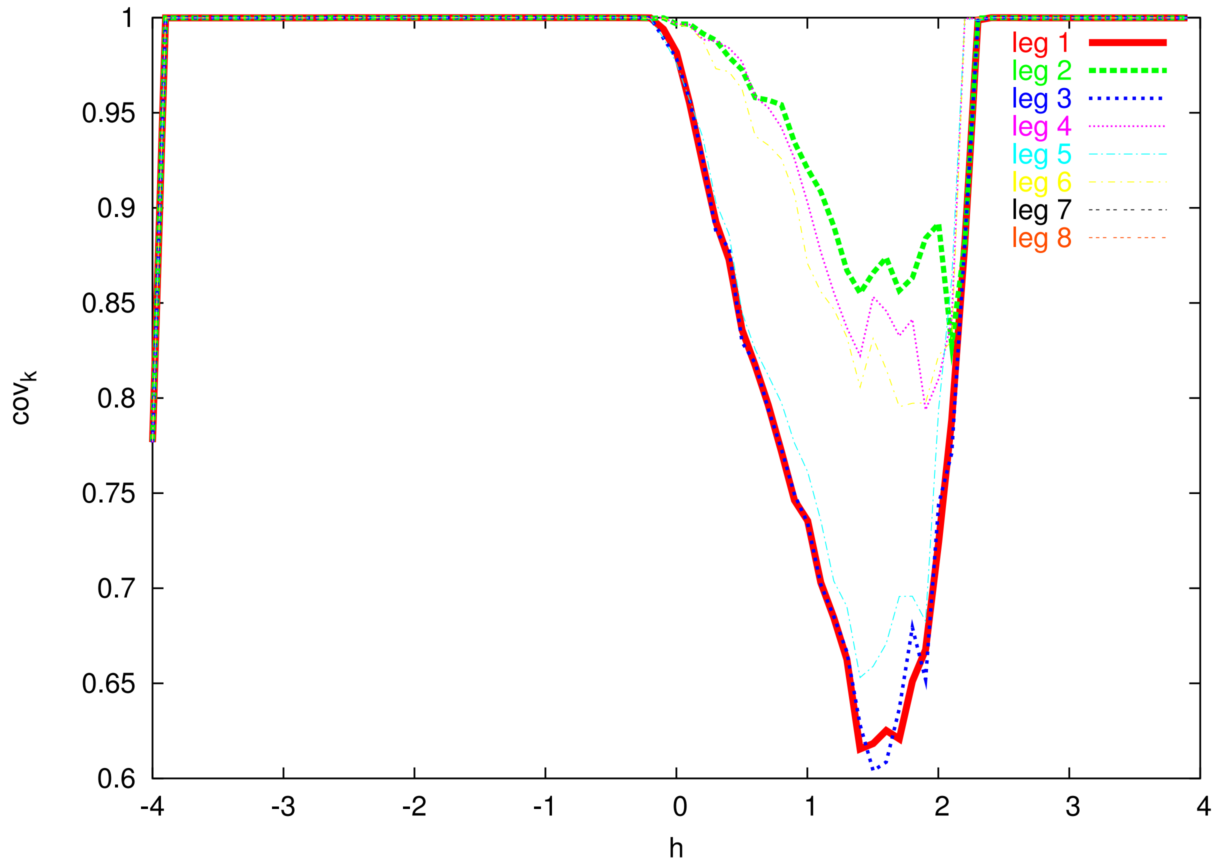
Effect of bound disorder

The previous graphs had no disorder in the couplings, just in the orientations of the easy axes. If we make the disorder large, the RPM/CPM difference remains:



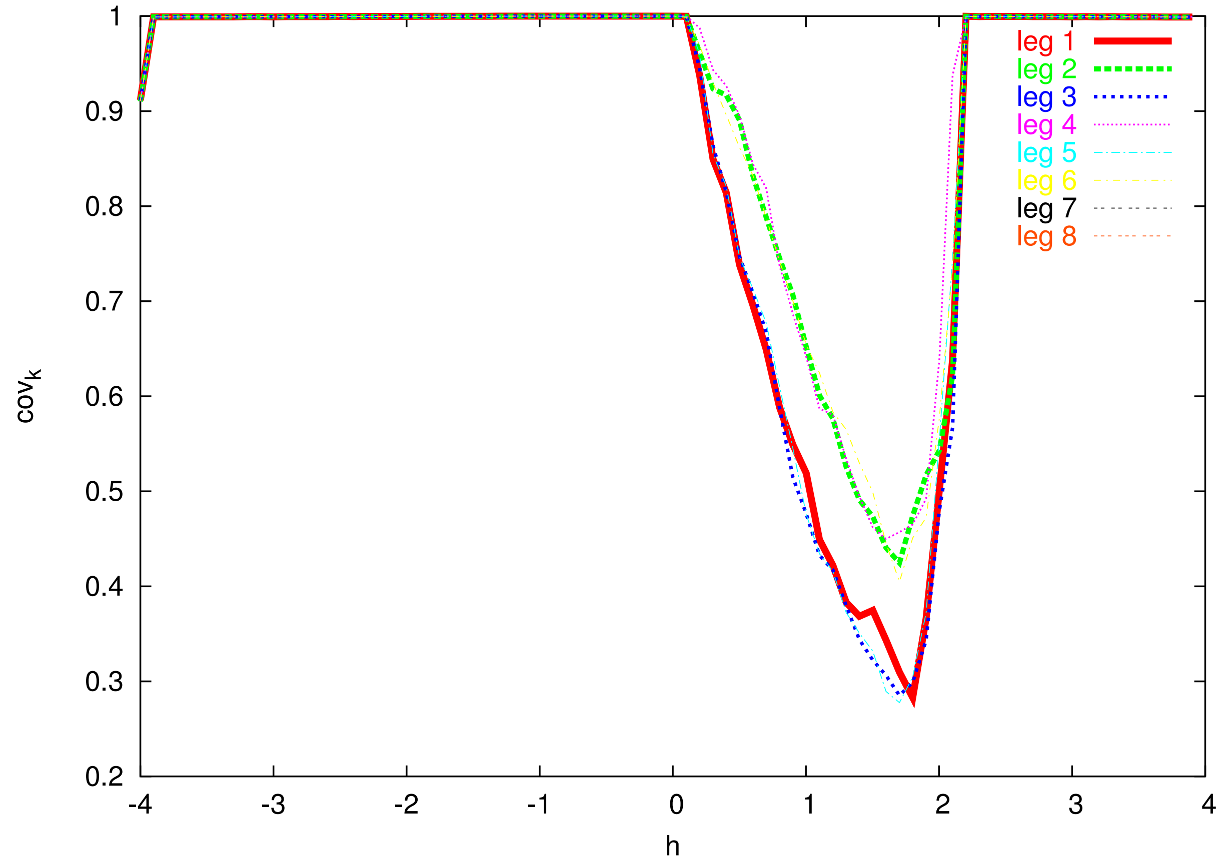
Effect of orientational disorder

Earlier pictures had no disorder in the couplings, just in the orientations of the easy axes. If we go back to no bound disorder but crank up the orientational disorder by a factor of 10, a CPM/RPM difference remains but it looks very different than the experiments:



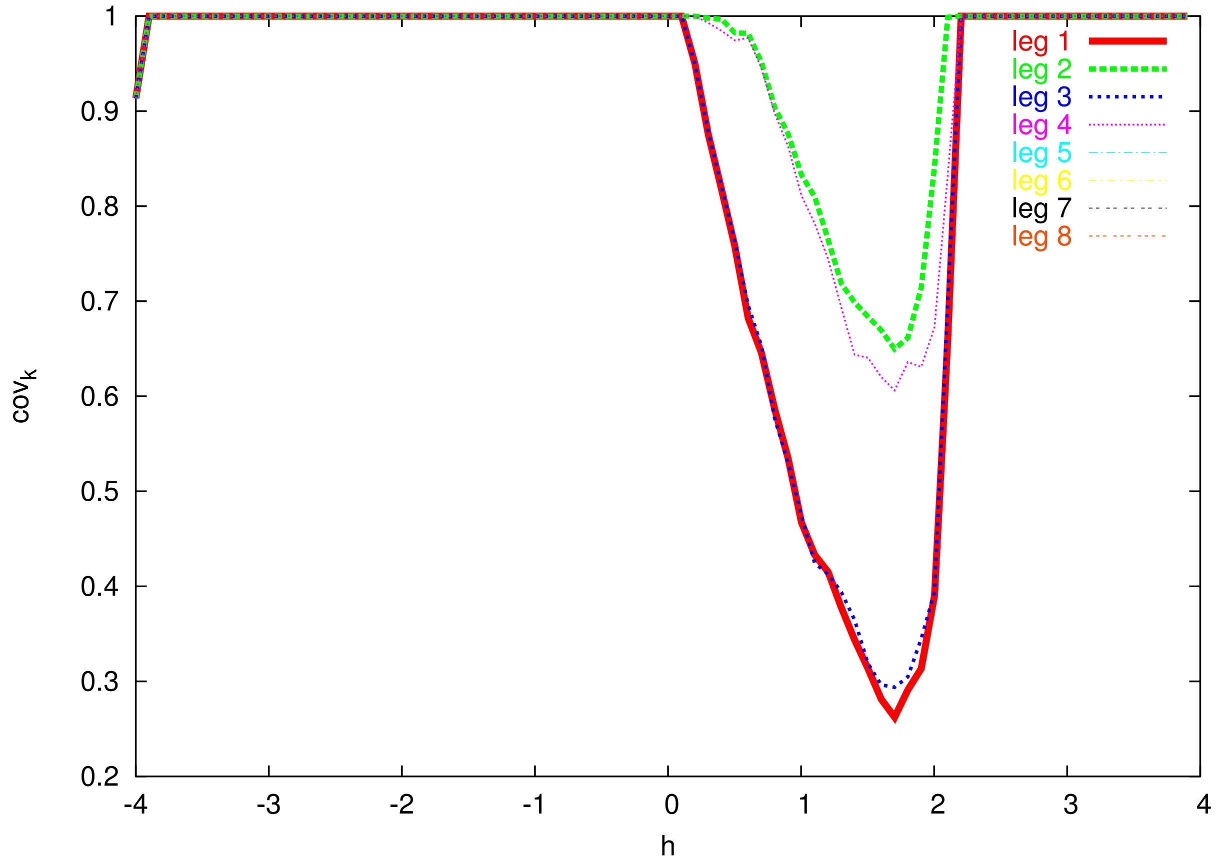
Extremely low temperature

An rpm/cpm difference similar to experiments

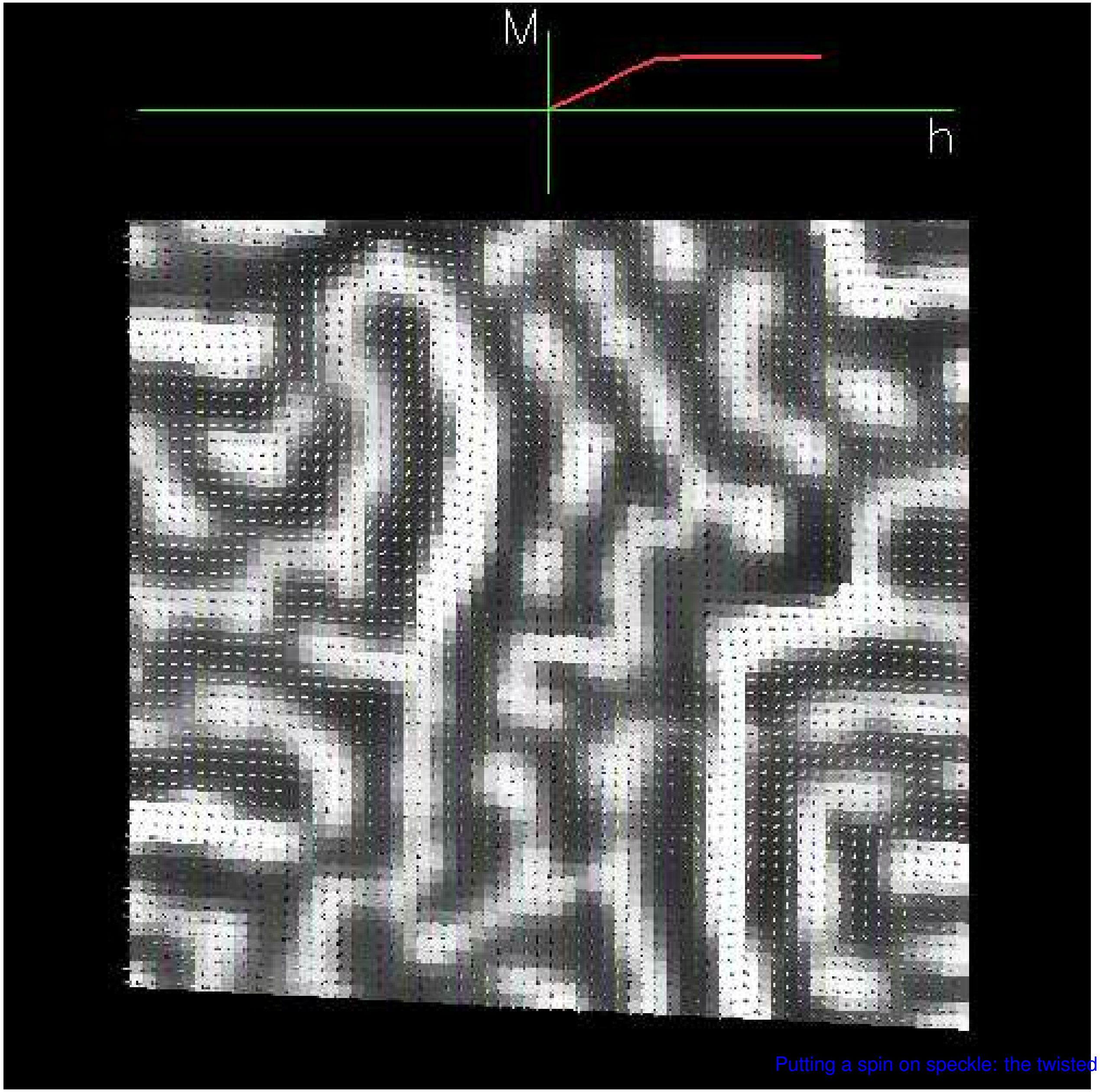


Extremely low temperature

The same parameters but .001 of the temperature



Example configuration



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However it can be done. Just a random field with 4% the spin-spin coupling can produce results similar to the experiments.

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Of course not!

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- The experiment might be wrong

  < .00002%